Quarterly Performance Report
March 30, 1993 - June 29, 1993
Grant No. N00014-92-J-4096

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I. FUNCTIONAL ANALYSIS DESCRIPTION

Appendix A is an initial functional flow block diagram and descriptions for the planned assembly system. Determination of functional requirements has led to specific research issues to be investigated.

II. HUMAN FACTORS ISSUES

Considering Automation

The primary purpose of providing designers with automatic assembly generation is to aid the designer. However, whenever automation is considered, the impact on the human user must be considered. In some situations automation may actually cause degradation in performance if it is not implemented correctly. For example, operators of some systems which are automated are required to perform monitoring functions. Boredom may interfere with their ability to perform their task. Another problem is that operators may not completely understand the options or functions enough to make appropriate decisions because they do not form appropriate mental models of the system. With design tasks, we must be sure not to take away the ability of the user to solve unique problems creatively. An extremely rigid system could interfere with creativity. Determining how automation affects the operator is very important; however, it is often difficult to investigate the affects on creativity. We must consider the affects our automated functions have on designers performance and carefully choose and evaluate functions that are automated.

Types of Representations Appropriate For Each Stage of Design

The designer will provide input during several assembly design stages including the following:

a) Specification of mating relationships,
b) Specification of user defined precedence relationships such as liaison, questions, soft precedence relationships, and subassemblies,
c) Comparison of current product to previous products,
d) Confirmation and modification of assembly model and precedence relationship data,
e) Selection of subassemblies,
f) Confirmation and selection of sequences.

For each of these stages optimal visual representations will be explored. It is

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June 28, 1993

Dear Dr. Wachter,

Enclosed please find three copies of the quarterly performance report for the period 30 March to 29 June 1993, for Grant No N00014-92-J-4096.

Sincerely,

Jennie J. Gallimore
Wright State University

cc: Administrative Grants Officer
Director, Naval Research Laboratory
Defense Technical Information Center

important to determine what types of representations will be appropriate for each stage of design. In an experimental session reported by Balley (as cited in Rouse and Boff (3)), designers created different types of sketches at various stages of the design process. Balley states "Each of these appears to serve unique functions in aiding the design process."

Amount of Detail Displayed

When determining appropriate representations the amount of detail that is displayed must be considered. Some tasks may involve in-depth information which would require a detailed view of the product, while other tasks may be broader requiring less detail (detail may actually hamper progress of user in some tasks). As stated by Gorskv (4), "Concrete details not only do not assist it's (left hemisphere) functioning, but even interfere with it. For example, a schematic drawing of the object is often recognized better than the object itself by the left hemisphere, while the right hemisphere prefers realistic, minute pictures with a great number of details. The left hemisphere controls the logic of our actions, estimates time and causal relationships, thus enabling us to create a philosophical understanding of nature."

Considering the level of detail brings up the question of how much detail will be appropriate for each task. Is it possible to anticipate the level of detail needed for each task, or should the designer be allowed some flexibility to choose different levels of detail? If it appears helpful to allow the designer to vary the level of detail, a number of methods could be used, including windows and the fisheye technique.

Information Included in Less Detailed Representations

For representations with less detail, what information should be included? Attneave (12) reports that most of the information in a picture is contained in a small portion if the image. The information is contained along contours, where color (including brightness) changes abruptly and at points on the contour where the direction changes most rapidly. Therefore, it should be possible to create representations that contain only a small amount of detail but a lot of information.

When creating a less detailed figure, will a 2D representation be sufficient? Newsom and Spillers (13) state that designers like to use 3D pictures even in the early conceptual stage of design.

Data Representation Flexibility

In addition to allowing the designer to choose various levels of detail, it may be helpful to allow the designer to choose between a number of data representation types. Perhaps several could be useful at any design stage.

Representation of Whole Assembly

When a picture of the whole assembly sequence is desired, how should it be displayed so that the user knows what is being assembled at each stage? The display should avoid

representations that require the user to remember or visualize information. Rouse and Boff (3) state that "...humans are excellent at recognizing displayed patterns but relatively poor at recalling previously observed patterns." Also, the display should avoid requiring user to constantly refer to another diagram. The current representations of sequences in the literature exhibit these problems. They use diagrams containing nodes and links that represent parts and connections (sometimes using numbers or letters as indicators of which part or liaison). These graphs require the user to be very familiar with the numbers/letters and what parts they represent, or they require the user to refer frequently to a separate picture of the product to determine what the numbers/letters represent. Also, some of the graphs represent many sequences at one time which is too much information for the human to process at once.

Examples of these representations are given in:

a) Chen, 1991 (6)
b) Defazio and Whitney, 1987 (1)
c) Zeid, 1991 (2)
d) Homen De Mello and Sanderson, 1990 (7)
e) Baldwin, Abell, Lui, DeFazio and Whitney, 1991 (11)
f) Nevins and Whitney, 1989 (8)
g) Wang and Li, 1991 (9)
h) Delchambre, 1992 (10)

One solution to this problem would be to show a *sequence of boxes* with a picture of the product at it's current stage of assembly in each box. The picture would need to highlight what was being assembled at each stage. Some possible methods of highlighting assembled parts would be to use color, motion, or directed attention (or a combination of these).

If this solution is used, it would be desirable to show the whole sequence on the screen at one time. Newsom and Spillers (13) state that "... their (the designers studied) initial approach to a design problem would be characterized by abstract, global representations of the design. The verbal reports of the interviewees describe the initial phase of conceptual design as one in which rough nondetailed sketches were most useful. Theses sketches appeared to be representations that allowed the designer to study the form in a global manner instead of focusing on the details."

If it is not possible to show the whole assembly sequence on the screen at once, it will be necessary to use a technique to look over the design. Techniques could include scanning, windows, fisheyes, or projecting the image on a wall (14).

Comparison of Sequences

If several sequences are to be compared by the engineer, the sequences should be displayed, preferably at the same time. Rouse and Boff (3) state "If a designer has several ideas in mind, he typically cannot evaluate the relationships among them until they are made visible. A drawn external representation is a very important aid to the designer in making

spatial inferences."

In addition to comparing assembly sequences based on a physical representation, designers must compare assembly sequences based on abstract criteria such as difficulty of assembly, cost, handability, etc.. How do we provide visualizations of the sequences that enable designers to consider these non-visual criteria? One possibility that is being explored is to define parameters and use volume rendering techniques to provide a visualization of the n parameters most important to the designer. However, volume visualization requires large processing capabilities and is not typically available to the designer in real time. We are investigating a visualization package called Explorer on our current workstation.

Manipulation of Sequences and Assembled Product

It may be helpful to allow the designer to manipulate the sequences at some stage of the design process. Newsom and Spillers (13) state "The CAD tool needed and desired by the interviewees would incorporate the rough sketch function while still allowing the designer to depict the form in three-dimensional space. In addition, the designer should be able to manipulate the design in space while it is in a rough global representation." This is referring to design before the detailed design of parts, but may have some application in this project by allowing the designer to explore various design ideas for the assembly. It may also be helpful for analysis of floor layout for the assembly. In addition to being able to manipulate the design, it may be helpful to provide kinesthetic feedback through a device such as a data glove. This may give the designer a better understanding of the assembly sequence, especially if real parts are not available (parts still only in CAD system).

Manipulating the assembled product may also be useful. This may help the designer visualize the liaisons better when determining precedence relationships.

Providing the Designer with Options and Flags

It will be helpful to provide users with options and to flag the user concerning potential problems. This would free the operator from having to remember a lot of design rules and would help novice designers learn the rules used by experts. Rouse and Boff (3) state that " ... the issue of working memory, which limits humans from keeping track of more than a few things simultaneously without being aided." The information to enable the system to do this would need to be gathered from the literature and protocol analyses.

Summary

Planning an assembly sequence is an important part of product design. The assembly sequence can affect many factors such as the product cost, the assembly time, the ease of assembly, the needs for fixturing, the potential for damage during assembly, and the ability to do in house testing (1,2).

CAD/CAM systems can aid designers during this important design stage by providing them with visual representations of the assembly sequence. An external representation is very important to the design process. When designers are considering several ideas, they

typically can't evaluate the relationships between the ideas until they are made visible (3). Therefore, a system that displays visual models should provide useful design assistance to the engineer.

Given that a visual model of the assembly would be helpful, how should the information be displayed? One factor to consider is that the display should present images that are appropriate for the design task. It should not present images that are too abstract, because this would require the user to form mental images of the product during assembly. As stated by Rouse and Boff (3) "...humans are excellent at recognizing displayed patterns but relatively poor at recalling previously observed patterns." Also, the display should avoid overloading the user with too much information at once. Displays containing too much information or detail can actually hamper the progress of the user (4,5). Another point to consider is that the display should integrate information into a single display when possible. Displays requiring the user to jump between several diagrams to understand a concept should be avoided.

The current representations of sequences in the literature do not follow these human-computer interface concepts (1,2,6-11). They were created in order to explain certain assembly sequence theories and were not designed to provide a useful format for interactive design. They use diagrams containing nodes and links that represent parts and connections. On some diagrams, the parts or connections are labeled with numbers or letters. These graphs require the user to refer frequently to a separate picture of the product to determine what the numbers or letters represent. Also, some of the graphs represent hundreds of sequences at one time, which is too much information for the human to process at once.

Techniques for graphic presentation and human interaction should:

1) Minimize memorization
2) Present information in format that is intuitive, that is, take advantage of human's natural abilities.
3) Present information in a format that is compatible with the task at hand.
4) Reduce clutter (present only necessary info).
5) Create the interface in a way that allows the user to easily keep track of where he or she is and how to get from one "function" to another.
6) Give the user appropriate feedback to confirm that system is operating as expected.
7) Allow the user to recover gracefully from mistakes.
8) Provide an environment that enhances creativity.

One possibility for an interactive display would be to show a sequence of boxes containing an abstract picture of the product at the current stage of assembly. The picture would contain only enough detail to identify the important features of the parts. The diagram would highlight the part being assembled at each stage. Some possible methods of highlighting assembly parts would be to use color, animation, or directed attention. Providing a simple model of the product at each stage of design, would eliminate the need for the designer to memorize codes or visualize the product.

One of our research studies will be conducted to explore this display method. The independent variable for the study will be the sequence representation method. During the experiment, subjects will be asked to perform an assembly planning task using various sequence representation diagrams. The performance on these tasks will be the dependent variable. Because research has not been done in this area, it is not clear what dependent variables will be sensitive to differences in performance. Some possible dependent variables include, 1) time to accomplish the task, 2) number of correctly accomplished tasks, 3) subject preference.

The following is a list of the sequence representation types to be considered during this research.

a) Static Diagram

For this representation type the subject will be presented with a sequence of boxes containing an abstract image of the product at the various assembly stages, using color to highlight the part being assembled.

b) Static Diagram, Directed Attention

The subject will be presented with a diagram similar to a) except that the boxes will be presented one at a time, in the order of assembly. This may direct the user's attention to the various assembly stages and clarify the assembly process.

c) Animated Diagram

The subject will be presented with a diagram similar to b) except that the assembly will be animated to emphasize the assembly process

d) Detailed Diagram

The diagram will be similar to a), b), or c) except that the boxes will contain detailed pictures of the parts

e) Physical Model, Visual Only

The subject will be shown a physical model of the product instead of the computer display. The user will be allowed to look at the model but not touch it (compare performance with computer to performance with a physical object)

f) Physical Model, Visual and Kinesthetic

This presentation will be similar to e) except that the subject will be allowed to handle the model (determine effect of kinesthetic information)

g) User Selection of method

The subject will be allowed to select from the above methods to see which are used most and for what tasks.

<u>Graph Drawing</u>

We have studied various two-dimensional graph drawing schemes, such as layered graphs, radial graphs, and orthogonal grid drawings which are pertinent to the optimal assembly

sequence generation task. We have also successfully implemented an automatic graph drawing program based on the criteria of edge (link) crossing minimization and graph symmetry. In particular, an initial implementation of three-dimensional optimal graph drawing program was completed.

The basic idea behind the optimal graph drawing is a relaxation based algorithm to minimize certain energy criteria imposed on the graph. The links among nodes are considered as springs with their resting lengths depending on the size of the drawing window as well as the minimum distance traversed from one node to the other. With other special types of graphs, such as layered graphs or radial graphs, additional constraints are further imposed in the minimizing criteria. The visual effectiveness of the optimal graphs, however, needs to be further studied and justified.

The 3D graph drawing increases the dimensionality of the visual perceptual space which in return enables the operator to visualize and manipulate the abstract graph at greater complexity. The 3D graphs, however, require additional graphics rendering, animation and interaction facility to fully explore the visualization of abstract relations. Our next step will be porting the 3D drawing codes to the newly acquired SGI graphics engine and expanding drawing primitives for the nodes as well as the links of the graph.

We have also looked into the volume rendering feature of SGI Explorer visualization package as well as it's data formats. In the later stage of the optimal assembly sequence generation, the task of visualizing and analyzing all feasible assembly sequences will be transformed into a visualizable multivariate space. The parameters of the space are usually cost or optimality related indices. Volume rendering techniques are used to increase the effectiveness of visual perception when the number of parameters is at least three.

III. PROTOCOL ANALYSIS

To obtain the designer' model and strategy of assembly planning, we first visited design engineers at NCR. Those engineers design ribbon cassettes which are used in printers and cash registers. The design engineers consider product assembly mainly from the economic standpoint. One concern is how to simplify the design of ribbon cassettes for easy assembly. A common solution to design for assembly is to reduce the number of parts for minimum number of assembly operations and thus minimum manufacturing cost. Since ribbon cassettes are composed of less than 20 parts, most assembling operations of ribbon cassettes are done manually by operators. Considering the flexibility operators have, the design engineers would rather leave assembly planning to operators once a product design is determined. Hence, the design engineers at NCR can not provide us a great deal of knowledge about assembly planning.

We also met with another organization, Robbins & Meyers, to obtain the same information from their design engineers, however, the type of design work they perform does not present true assembly planning problems. Robbins & Meyers is a small company that designs pumps. The nature of this product is such that usually less than 50 parts are comprised to manufacture these pumps. The design engineers are not confronted with assembly planning problems due the fact that all pumps are basically comprised of the same

general part type and assembly sequence, the greatest difference being the material properties of the pump and the type of material being pumped. Therefore, their engineers are familiar with the assembly sequence to the extent that it is not an issue. This prevented us from obtaining the information necessary to complete this phase of the research.

We also met with design engineers at Whirlpool. Whirlpool makes a large number of products, many of which consist of in excess of 900 parts. The engineers have stated that assembly planning is an important issue due to the large number of parts used, as well as the fact that not all of the parts are made in-house, therefore, having to ensure parts made in-house can be assembled with parts made by other manufacturers. Whirlpool engineers and management have agreed to participate in this research effort. They would like to benefit from a system that helps engineers plan for assembly.

The protocol analysis will be conducted in two phases. The first phase includes a number of on-site interviews with the design engineers to get an overview of their activities relating to assembly planning. In the second phase, the design engineers will be invited to the human factors engineering laboratory to participate in a controlled experiment for protocol analysis. In the experiment, the design engineers will be asked to generate an assembly plan for a product which is chosen by the experimenter. During assembly planning, the design engineers will be asked to verbalize their thinking process. Their verbal report will then be evaluated and analyzed to provide data which reveal their model and strategy for assembly planning.

IV. ASSEMBLY GENERATION

Research has continued on the use of Interval Analysis in assembly planning. To apply Interval Analysis we suggest adopting Constructive Solid Modelling as the geometric model because it is convenient for geometry testing and easily captures the user's design.

The procedures to apply Interval Analysis are described as follows:

Step 1. Build a library of Inclusion Functions for the geometry models in the model library, such as cube, sphere, cylinder, ellipsoid..., and build a general Inclusion Function for user defined Boundary-Representation curves. These Inclusion Functions have parameters such as diameter for spheres, length for cubes etc.

Step 2. Construct operators of Inclusion functions, such as + - * /, etc.

After completion of Steps 1 and 2 we can then build a procedure that recursively subdivides the space and apply Inclusion Functions on each part to evaluate the boundary of that part on some specified interval until certain conditions are met. We can then evaluate the geometric result.

The Geometric model is a complete representation in the computer for a mechanical assembly. It tells the computer about the part sizes, orientations, and implicitly tells the computer about the topological relations among parts.

In terms of assembly representation, part sizes, orientations, and topological relations can be explicitly and implicitly represented. The geometric model can be stored as a set of parts with features, sizes, positions, and orientations. Geometric operations such as and, or, minus, difference, etc. allow us to construct the geometric model for the assembly.

Having the designer provide both geometrical and topological information about the assembly in the form of connection graphs during the design stage is impractical. To make the system more user-friendly, we propose that the planning system should be able to function primarily based on the geometric model, and require the user to interact at more important stages when sophisticated procedures are used such as determining topological information for non-linear or non-monotone assembly.

To evaluate the "goodness" of a sequence, we consider such criteria as the orientation of the assembled part or the frequency of tool changes. Additional criteria must be associated with the specific working environment.

V. GOALS FOR THE PERIOD JUNE 30 - SEPTEMBER 29, 1993

Algorithm Development

Develop algorithms for generation of feasible sequences, including:

a) Determine a data structure for the geometric detection routine.

b) Develop obstacle detection algorithm.

c) Implement an algorithm to find out feasible sequences for monotone assembly, based on geometric constraints.

Visualization Research

a) Conduct experimentation on abstract graphing techniques for providing users with initial visualizations of different assembly sequences. An experiment has been defined. (Examples were summarized in the previous section). Programming and data collection will take place during the next quarter.

b) To develop the three-dimensional graph drawing program on the SGI machine. The graphics hardware on the SGI machine enables us to visualize the abstract graphs in 3D with real time interactive animated display. Overlaid graphics combining abstract relations with real product parts will also be examined.

c) To establish initial data exchange formats between textual descriptions in the database and the graphical representation of three-dimensional drawings.

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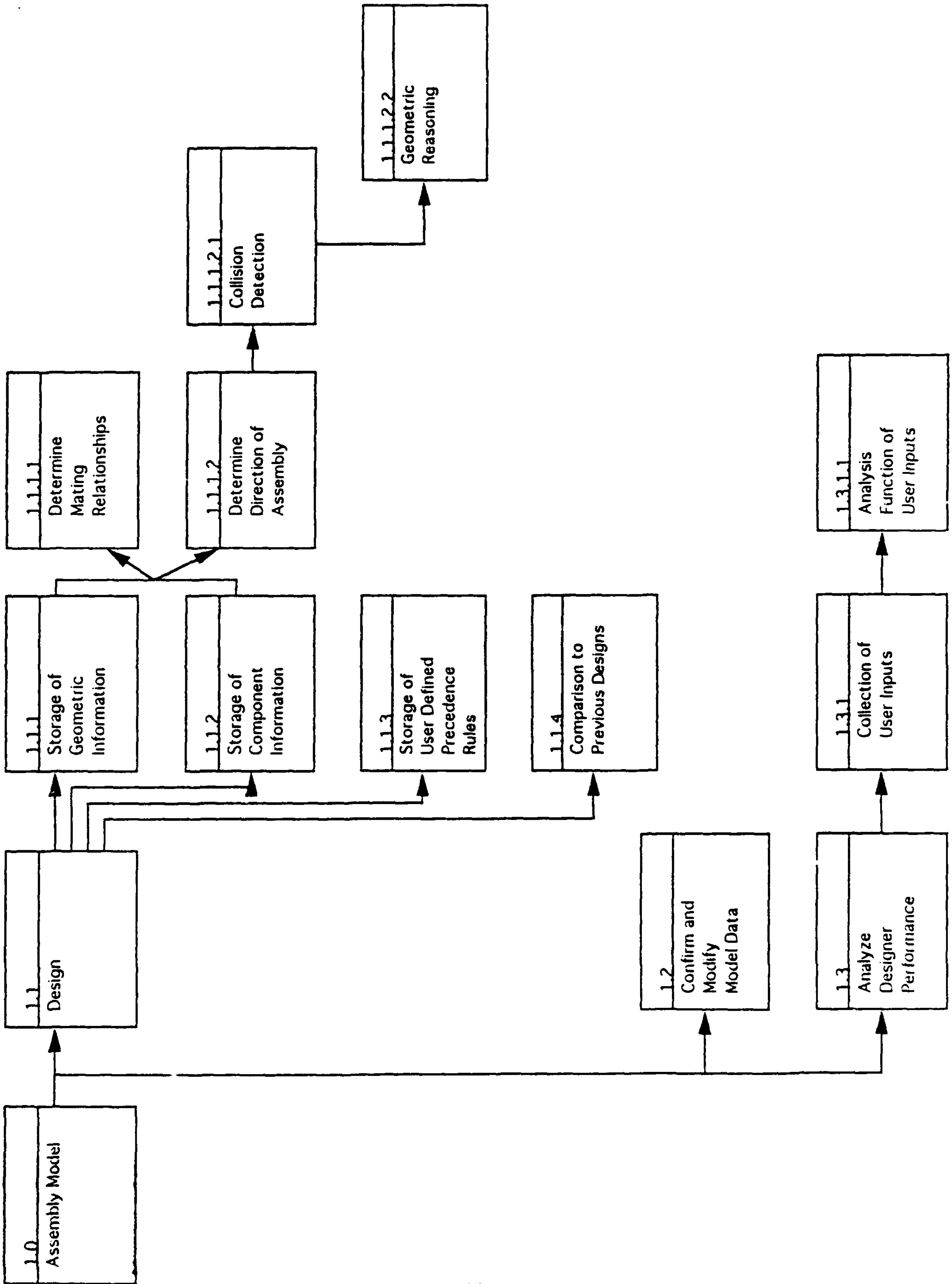
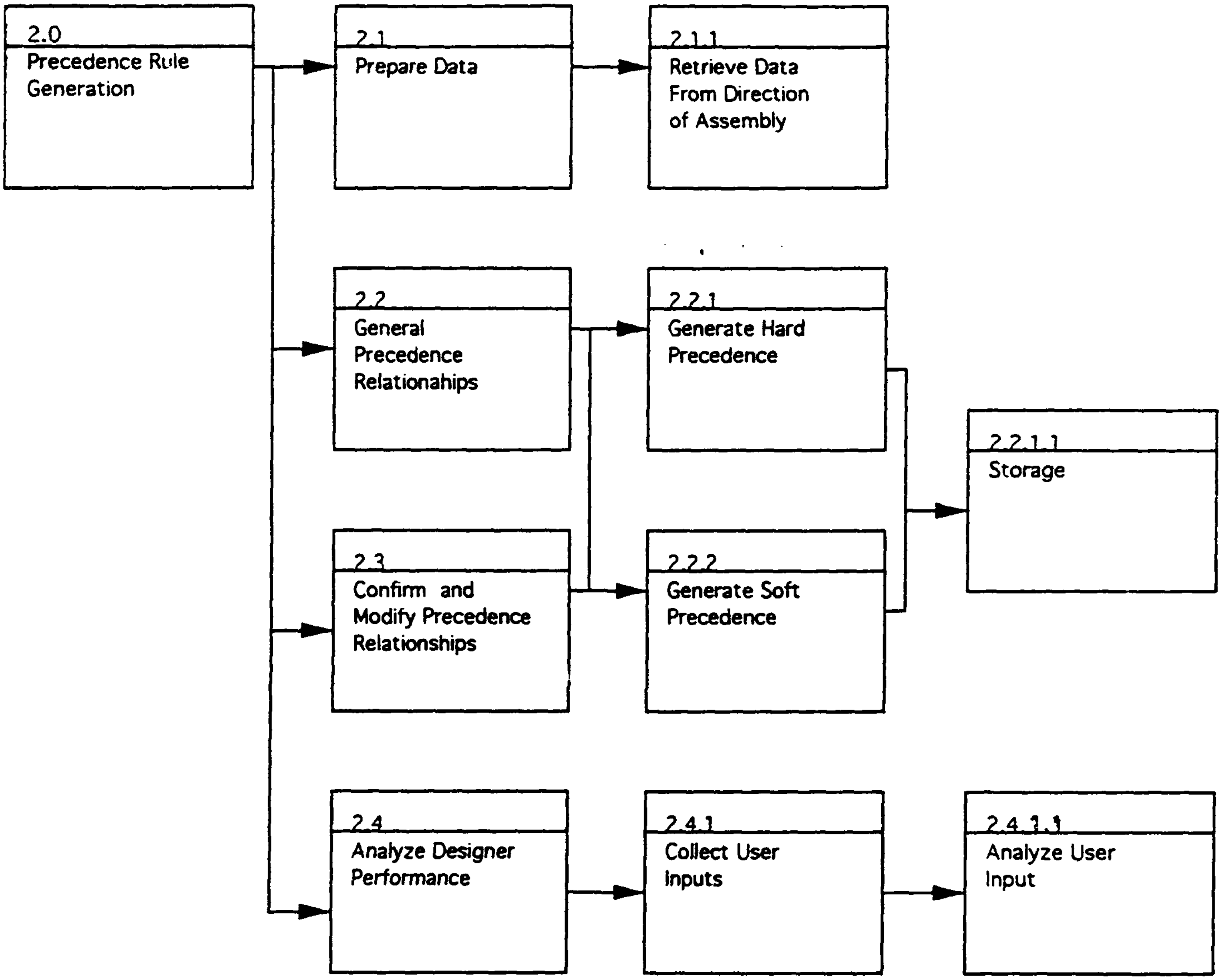
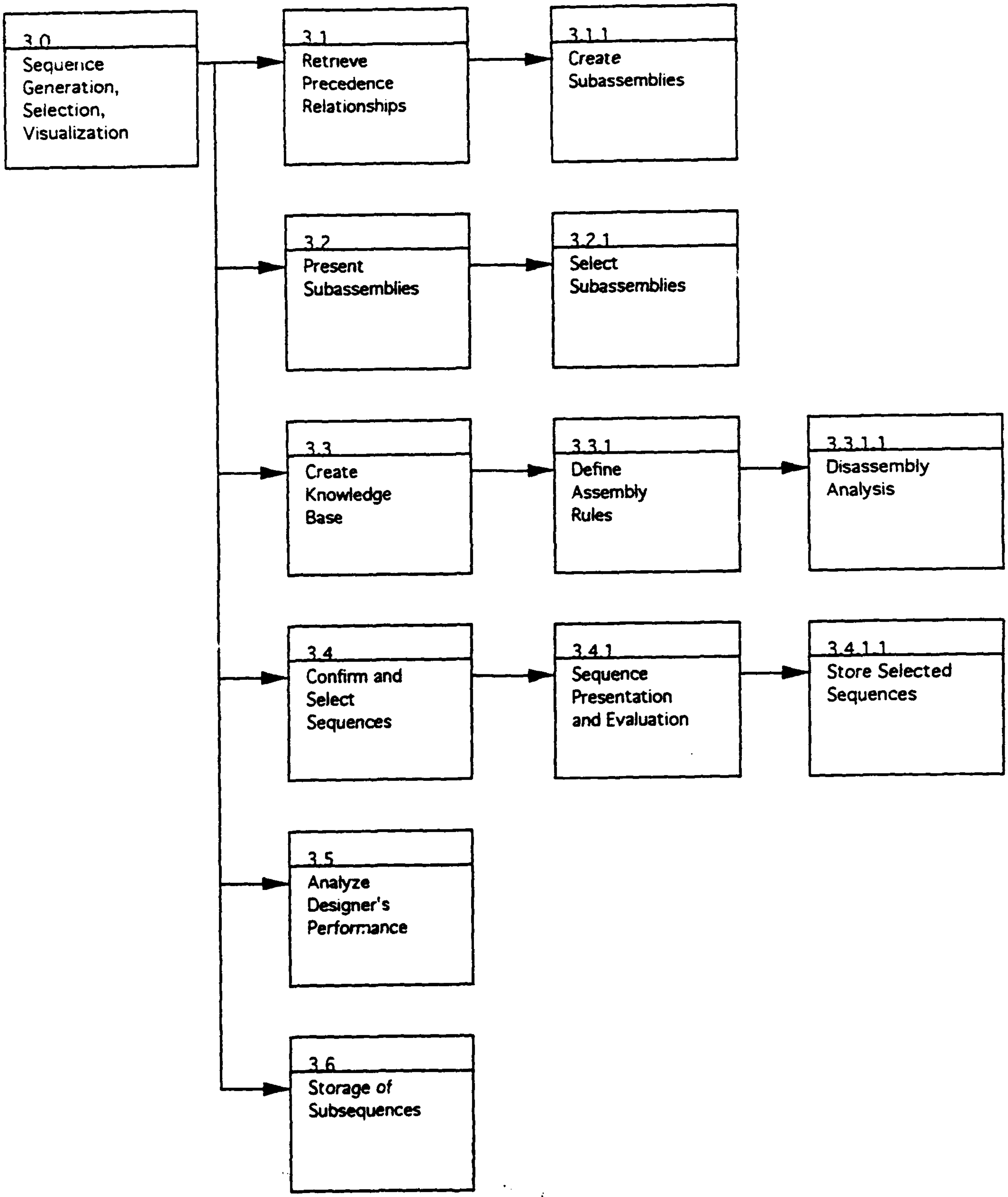

1.0 Assembly Model
1.1 Design
1.1.1 Storage of Geometric Information
1.1.2 Storage of Component Information
1.1.3 Storage of User Defined Precedence Rules
1.1.4 Comparison to Previous Designs
1.1.1.1 Determine Mating Relationships
1.1.1.2 Determine Direction of Assembly
1.1.1.2.1 Collision Detection
1.1.1.2.2 Geometric Reasoning
1.2 Confirm and Modify Model Data
1.3 Analyze Designer Performance
1.3.1 Collection of User Inputs
1.3.1.1 Analysis Function of User Inputs


2.0
Precedence Rule Generation
2.1
Prepare Data
2.1.1
Retrieve Data From Direction of Assembly
2.2
General Precedence Relationahips
2.2.1
Generate Hard Precedence
2.2.1.1
Storage
2.3
Confirm and Modify Precedence Relationships
2.2.2
Generate Soft Precedence
2.4
Analyze Designer Performance
2.4.1
Collect User Inputs
2.4.1.1
Analyze User Input


3.0
Sequence Generation, Selection, Visualization
3.1
Retrieve Precedence Relationships
3.1.1
Create Subassemblies
3.2
Present Subassemblies
3.2.1
Select Subassemblies
3.3
Create Knowledge Base
3.3.1
Define Assembly Rules
3.3.1.1
Disassembly Analysis
3.4
Confirm and Select Sequences
3.4.1
Sequence Presentation and Evaluation
3.4.1.1
Store Selected Sequences
3.5
Analyze Designer's Performance
3.6
Storage of Subsequences

Functional Descriptions

1.0 ASSEMBLY MODELLING

Purpose: To collect and store assembly modelling design information and constraints such that precedence rule generation can be accomplished. This function includes geometric information, component information, user defined precedence relationships, direction of assembly, etc... The user will interact with the system at this level to determine important constraints for their particular product.

SUBFUNCTIONS

1.1 Design

1.1.1 Storage of geometric information
(Taken directly from CAD drawings)

1.1.1.1 determine mating relationships

1.1.1.2 determine direction of assembly

1.1.1.2.1 perform collision detection

1.1.2 Storage of component information
(Eg., how component affects assembly, handability, stability, is it a base part?, etc..)

1.1.2.2 develop geometric reasoning

1.1.3 Storage of user defined precedence rules
(Input from operator regarding constraints on sequences)

1.1.4 *Comparison* to previous designs
This subfunction will provide the user with the ability to refer to previous designs to help with decision making. This subfunction will not be automated.)

1.2 Confirm and Modify Model Data

Purpose: To allow user to confirm model inputs and make modifications. Verification of inputs will also be provided by the computer to provide suggestions to the user.

1.3 Analyze Designer Performance

Purpose: To determine what functions the designer uses and how well the system is aiding the designer during the modelling stage.

1.3.1 Collect user inputs

1.3.1.1 analyze user inputs

2.0 PRECEDENCE RULE GENERATION

Purpose: To develop hard and soft rules for generation of feasible assembly sequences.

2.1 Prepare Data

2.1.1 Retrieve data from direction of assembly (1.1.1.2)

2.2 General Precedence Relationships

2.2.1 Generate Hard Precedence Rules

2.2.2 Generate Soft Precedence Rules

2.2.2.1 storage of rules

2.3 Confirm and Modify Precedence Relationships
Designer should have choice of fully automated confirmation function or manual validation of rules.
2.4 Analyze Designer Performance
2.4.1 Collect user input
2.4.2.1 analyze user input

3.0 SEQUENCE GENERATION, SELECTION, VISUALIZATION

3.1 Retrieve Precedence Relationships
3.1.1 Create subassemblies
3.2 Present Visualization of Subassemblies
(manual selection, automatic selection, or combination manual/automatic)
3.2.1 Select subassemblies
3.3 Create Knowledge Base
3.3.1 Define assembly rules
3.3.3.1 disassembly analysis
3.4 Confirm and Select Sequences
(Provide design with choice of sequences to generate from upper level subassembly)
3.4.1 Sequence presentation and evaluation
(Examples: awkwardness, reorientation, fixturing, stability, breakage, safety, etc.)
3.4.1.1 store selected sequences
3.5 Analyze Designer Performance
3.6 Storage of Subsequence